# Polarization spectroscopy of x-ray transitions from beam-excited highly charged ions

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Polarization spectroscopy of x-ray lines represents a diagnostic tool to ascertain the presence of electron beams in high-temperature plasmas. Making use of the Livermore electron beam ion trap, which optimizes the linear x-ray line polarization by exciting highly charged ions with a monoenergetic electron beam, we have begun to develop polarization diagnostics and test theoretical models. Our measurement relies on the sensitivity of crystal spectrometers to the linear polarization of x-ray lines which depends on the value of the Bragg angle. We employed two spectrometers with differing analyzing crystals and simultaneously recorded the $K$-shell emission from heliumlike $Fe^{24+}$ and lithiumlike $Fe^{23+}$ ions at two different Bragg angles. A clear difference in the relative intensities of the dominant transitions is observed, which is attributed to the amount of linear polarization of the individual lines. *© 1997 American Institute of Physics.* [S0034-6748(97)67601-7]

## I. INTRODUCTION

Excitation by unidirectional electrons produces polarized line radiation.[1,2] As a result, the presence of electron beams in high-temperature plasmas can be ascertained by analyzing the degree of polarization of the emitted radiation. For this purpose, polarization spectroscopy of x-ray lines from highly charged ions is especially useful, because such lines are typically less susceptible to the effects of magnetic and electric fields than, for example, optical lines from low ionization stages that could mask the polarizing effects of beam excitation. Polarized x-ray emission has been used to diagnose directional electrons in laser-produced plasmas,[3,4] and the Sun;[5–7] it may also be used to diagnose and nonthermal electrons in tokamaks, for example, during wave heating experiments.[8]

X-ray line polarization is maximized in electron beam x-ray sources, such as an electron beam ion trap (EBIT), where highly charged ions are excited by a monoenergetic electron beam. Such sources are, therefore, ideal for testing theory and developing plasma-polarization spectrometers. Using an EBIT, measurements of the polarization of the x-ray line emission from highly charged heliumlike ions have been reported for $Sc^{19+}$ and $Fe^{24+}$.[9,10] These measurements have verified the predictions based on relativistic distorted-wave calculations, such as those reported by Inal and Dubau[11] or Zhang, Sampson, and Clark.[12]

In the following, we present a measurement of the polarization of the heliumlike and lithiumlike iron $K$-shell emission generated by excitation with a monoenergetic electron beam at the Livermore EBIT facility. The line emission was analyzed using two crystal spectrometers, which concurrently recorded spectra in a dispersion plane perpendicular to the beam direction. The first spectrometer used a LiF(220) crystal with lattice spacing $d=1.424$ Å and operates at a nominal Bragg angle of 41°. The second used a Si(220) crystal with lattice spacing $d=1.920$ Å and operates at a nominal Bragg angle of 29°. Because of the polarization-sensitive dependence of the reflection properties of x-ray crystals on Bragg angle, different line ratios were obtained with the two spectrometers, which were in accordance with predictions. The present measurement confirms and complements previous measurements of the polarization of the $Fe^{24+}$ line emission that were carried out using LiF(200) and quartz(203) crystals;[10] it provides a value for the polarization of the lithiumlike resonance line, and illustrates the two-crystal technique for polarization spectroscopy.

## II. EMITTED LINE EMISSION

Assuming quasistationary ions, the two intensity components of a line emitted by ions excited in the collision with monodirectional electrons depend on the observation angle $\vartheta$ relative to the direction of the electron beam. Following the prescription by Steffen and Alder,[13] the two components of linearly polarized line radiation from a cylindrically symmetric source emitting multipole radiation described by a single multipole operator are given by

$$I_{\parallel}(\vartheta)=\frac{\epsilon}{2}\sum_{\lambda=\mathrm{even}} B_\lambda A_\lambda[P_\lambda(\vartheta)+\Gamma(\kappa)f_\lambda P_\lambda^2(\vartheta)] \qquad (1)$$

and

$$I_{\perp}(\vartheta)=\frac{\epsilon}{2}\sum_{\lambda=\mathrm{even}} B_\lambda A_\lambda[P_\lambda(\vartheta)-\Gamma(\kappa)f_\lambda P_\lambda^2(\vartheta)]. \qquad (2)$$

Here, $I_\parallel$ denotes the intensity of light with electric field vector parallel to the beam direction and $I_\perp$ the intensity of light with electric field vector perpendicular to the beam direction. $B_\lambda$ is the orientation parameter, $A_\lambda$ is the angular distribution coefficient, and the product $A_\lambda\Gamma(\kappa)f_\lambda$ describes the linear polarization parameter. $P_\lambda(\vartheta)$ and $P_\lambda^2(\vartheta)$ represent the Legendre and associated Legendre polynominal, respectively; $\lambda$

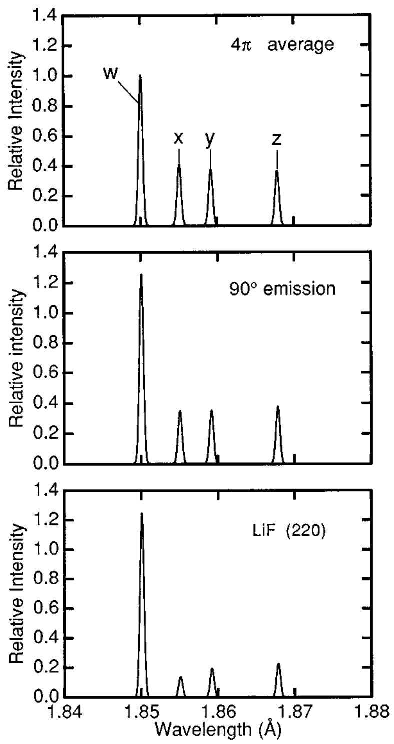


FIG. 1. Predicted intensities of the four $K\alpha$ lines from heliumlike $Fe^{24+}$ excited by a 6850 eV electron beam. Top: unpolarized, $4\pi$-averaged emission. Middle: polarized emission at an observation angle $\vartheta=90°$, i.e., in the plane perpendicular to the electron beam direction. Bottom: observed emission after analysis with a LiF(220) crystal at an observation angle $\vartheta=90°$.

is the multipole order of the emitted radiation; $\epsilon$ is the total intensity of the line emission, which depends on the electron and ion density, and the excitation cross section of the line.

Evaluating the two intensity components at an observation angle $\vartheta=90°$, allows calculation of the expression for the linear polarization $P$:[2]

$$P=\frac{I_{\parallel}(90°)-I_{\perp}(90°)}{I_{\parallel}(90°)+I_{\perp}(90°)}. \tag{3}$$

The polarizations calculated near threshold for electron-impact excitation of the four lines observed in heliumlike iron are:[10,11] $P_w=0.599$ for the electric dipole ($E1$) transition $1s2p\ ^1P_1+\rightarrow 1s^2\ ^1S_0$, labeled $w$; $P_y=-0.192$ for the $E1$ transition $1s\ 2p\ ^3P_1\rightarrow 1s^2\ ^1S_0$, labeled $y$; $P_z=-0.074$ for the magnetic dipole ($M1$) transition $1s2s\ ^3S_1\rightarrow 1s^2\ ^1S_0$, labeled $z$; and $P_x=-0.515$ for the magnetic quadrupole ($M2$) transition $1s2p\ ^3P_2\rightarrow 1s^2\ ^1S_0$, labeled $x$. The polarization calculated for the resonance line $1s2s2p\ ^2P_{3/2}\rightarrow 1s^2 2s\ ^2S_{1/2}$ in lithiumlike iron, labeled $q$, is $P_q=+0.35$.[14]

Figure 1 contrasts the predicted intensity of heliumlike iron lines emitted at $\vartheta=90°$, i.e., in the plane perpendicular to the direction of the electron beam, with the $4\pi$-averaged, or unpolarized, emission. The emission of line $w$ at $\vartheta=90°$ is enhanced by 25% compared to the $4\pi$-averaged emission. By contrast, the emission of the two $1s-2p$ triplet lines is reduced. That of line $z$ is almost unchanged. The fact that the angular dependence of the emission of each of the four lines varies in a different manner is very useful for diagnostic purposes. The measurements presented in the following have been performed at $\vartheta=90°$.

## III. OBSERVED LINE EMISSION

The intensity of an x-ray line observed with a crystal spectrometer is

$$I^{\mathrm{obs}}=R_{\parallel}I_{\parallel}+R_{\perp}I_{\perp}, \tag{4}$$

where $R_{\parallel}$ and $R_{\perp}$ are the integrated crystal reflectivities for x rays polarized perpendicular and parallel to the plane of dispersion. The ratio $R_{\perp}/R_{\parallel}$ depends on the Bragg angle $\theta$. In general, $R_{\perp}/R_{\parallel}=|\cos^m(2\theta)|$, where $1\leq m\leq 2$.[15] The two limiting values $m=1$ and $m=2$ correspond to the case of perfect crystals and mosaic crystals, respectively. While most analyzing crystals are neither perfect nor mosaic, several types are available that can be considered perfect for practical purposes. These include x-ray crystals made of quartz, silicon, or germanium, and setting $m=1$ provides a good description of their relative reflection properties. The actual value is somewhat less than this value because of absorption. Calculations for the relative crystal reflectivities of perfect crystals that take absorption into account have recently been published by Henke, Gullikson, and Davis.[16]

Because analyzing crystals reflect the two polarization components differently, the intensity observed with crystal spectrometers differs from the emitted intensity. At $\theta=45°$, $I_{\perp}$ vanishes and only $I_{\parallel}$ is observed. At Bragg angles away from 45°, both components of a given line are observed. Because the linearly polarized lines in heliumlike iron have differing ratios of $I_{\perp}$ and $I_{\parallel}$, they are affected differently when analyzed with a Bragg crystal spectrometer. This is illustrated in Fig. 1 where the predicted intensity of the lines emitted at $\vartheta=90°$ is compared to the predicted intensity after analysis with a LiF(220) crystal. In this calculation, we assume $R_{\perp}/R_{\parallel}=0.12$, as calculated by Henke, Gullikson, and Davis.[16] Lines with $I_{\perp}>I_{\parallel}$ are generally reduced relative to lines with $I_{\perp}<I_{\parallel}$. As a result, the triplet lines are markedly reduced relative to the singlet line. Recording the line emisision with two different analyzing crystals at two different Bragg angles thus makes it possible to infer the value of each intensity component of a given line and to infer its polarization. In the present study, we employed a LiF(220) crystal with lattice spacing $d=1.424$ Å and a Si(220) crystal with $d=1.920$ Å. The corresponding Bragg angles were $\theta=41°$ and 29°, respectively.

Each crystal in the present measurement was bent to a 30 cm radius of curvature and employed in one of two von Hámos-type spectrometers[17,18] that simultaneously viewed the EBIT trap in the plane perpendicular to the beam direction.

The results of the present measurement are shown in Fig. 2. The electron beam energy was set to 6.85 keV in our measurement, i.e., to a value about 150 eV above the threshold for electron-impact excitation of the heliumlike transitions. As expected from the difference in the relative crystal reflectivities, the relative intensities of the four heliumlike lines differ notably in the two spectra. The triplet lines are

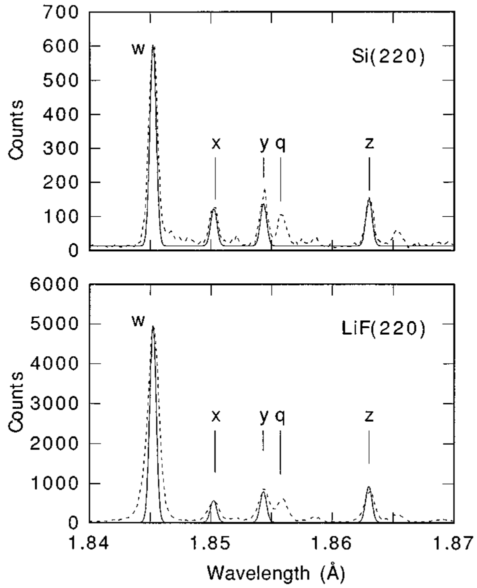


FIG. 2. Crystal-spectrometer spectra of lines *w*, *x*, *y*, and *z* in Fe XXV and line *q* in Fe XXIV excited by a 6850 eV electron beam (dashed lines). (Top) spectrum obtained with a LiF(220) crystal at a Bragg angle of 41°; (bottom) spectrum obtained with a Si(220) crystal at a Bragg angle of 29°. Unlabeled features are from transitions in Fe XXIV and Fe XXIII formed by innershell excitation. The predicted spectral intensities (solid lines) are superimposed for comparison.

suppressed relative to the singlet line intensity in both spectra, but this suppression is much more pronounced in the spectrum obtained with the LiF(220) crystal.

Overall, the counting efficiency of the Si(220) spectrum is about ten times less than that of the LiF(220) spectrum. This is the result of higher integrated reflectivities of the LiF crystal. At the same time, the spectral resolving power of the LiF measurement ($\lambda/\Delta\lambda=1500$) is lower than the Si measurement ($\lambda/\Delta\lambda=2200$).

## IV. COMPARISON BETWEEN EXPERIMENT AND THEORY

For comparison between experiment and theory, we have plotted the predicted line emission superimposed on the experimental data in Fig. 2. The calculations assume $R_\perp/R_\parallel=0.48$ for Si(220) and $R_\perp/R_\parallel=0.12$ for LiF(220), as calculated by Henke, Gullikson, and Davis.[16] Good qualitative agreement between the predicted and measured spectra is found, confirming the predicted angular dependence and polarization of the four heliumlike lines.

Using the iterative analysis procedure developed in Ref. 10 where cross normalization of the measured spectra is accomplished based on the intensity of line *z*, we can infer the polarization of each line and make a quantitative comparison with theory. We find $P_w=+0.80^{+0.20}_{-0.30}$, $P_x=-0.45^{+0.15}_{-0.13}$, $P_y=-0.14^{+0.17}_{-0.12}$, and $P_z=-0.067^{+0.015}_{-0.015}$, as summarized in Table I. The uncertainty limits are dominated by statistics. Within the uncertainty limits, the measured values are fully in accordance with the theoretical values and those measured previously. Assuming a value of $R_\perp/R_\parallel=0.04$ for a mosaic LiF(220) crystal, the magnitude of the inferred polarizations is reduced to $P_w=+0.54$, $P_x=-0.37$, $P_y=-0.09$, and

TABLE I. Comparison of calculated and measured values of the polarization of lines *w*, *x*, *y*, *z*, and *q* at an excitation energy about 100–150 eV above threshold. Radiative cascade effects are included in the theoretical predictions for line *z*.

| Line | Theory (Refs. 11 and 14) | Theory (Ref. 10) | Measurement (Ref. 10) | Present measurement |
|---|---|---|---|---|
| $P_w$ | +0.584 | +0.599 | $+0.56^{+0.17}_{-0.08}$ | $+0.80^{+0.20}_{-0.30}$ |
| $P_x$ | −0.518 | −0.515 | $-0.53^{+0.05}_{-0.02}$ | $-0.45^{+0.15}_{-0.13}$ |
| $P_y$ | −0.196 | −0.192 | $-0.22^{+0.05}_{-0.02}$ | $-0.14^{+0.17}_{-0.12}$ |
| $P_z$ | −0.078 | −0.074 | $-0.076^{+0.007}_{-0.007}$ | $-0.067^{+0.015}_{-0.015}$ |
| $P_q$ | +0.349 | | | $+0.18^{+0.20}_{-0.15}$ |

$P_z=-0.055$. These values lie within the statistical uncertainty limits given above and serve to illustrate the systematic uncertainties of the measurement given the fact that the actual value of $R_\perp/R_\parallel$ is unknown for LiF(220).

Because the two spectra were recorded concurrently, we can also infer the polarization of the lithiumlike resonance transition *q*, by cross normalizing the observations to the intensity of line *z*, i.e., the ion charge balance is the same and thus unimportant for the spectra recorded with either crystal. This was not possible in Ref. 10, where spectra were recorded sequentially and the charge balance had changed. We find $P_q=+0.18^{+0.20}_{-0.15}$. This is consistent with the theoretical value of +0.35, as summarized in Table I. Other lines evident in the spectra in Fig. 2 are too weak to infer a meaningful value for their polarization.

The agreement between measurement and theory illustrates quantitatively the reliability with which the polarization effects can be determined using the two-crystal technique. The uncertainties are larger than in the previous measurement[10] that used LiF(200) and quartz(203) crystals. The larger uncertainties are the result of the smaller differences in the relative crystal reflectivities of LiF(220) and Si(220) as compared to the LiF(200) and quartz(203) pair so that the inferred polarizations are more sensitive to the statistical uncertainties in the measured line intensities. Nevertheless, a clear dependence of the line intensities on the Bragg angle at which they are observed is found. The technique can easily be employed in situations where the amount of linear polarization is unknown and needs to be experimentally determined, e.g., in situations where excitation by nonthermal, directional electrons takes place in parallel with excitation by thermal, isotropic electrons. The accuracy with which the amount of polarization has been inferred in the present measurement was limited by statistics. Statistical limitations are often not as severe in other plasma sources such as tokamaks or laser-produced plasma sources, which are much more photon-intensive sources than an EBIT.

## ACKNOWLEDGMENTS

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